PARTICLE SEPARATION BY ULTRASONIC FORCES

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Abstract: A simple, effective device has been developed to separate mammalian cells from growth medium using the ultrasonic forces on suspended particles in a standing wave field. The ultrasonic force distribution in this acoustic separation device has been analyzed to provide a basis for further optimization of the separation system. Measurements of the force distribution in the liquid using a microscope-based imaging system were compared to laser interferometric measurements of the velocity amplitude distribution on the transducer and reflector surfaces of the ultrasonic resonator. The axial force followed the surface velocity, being highest near the center, and approaching zero near the walls. The transverse force distribution and the local grid-like surface amplitude variation had similar characteristic wavelengths. These results suggest that the force distribution is directly related to the reflector and transducer amplitude distributions. A simple model relating the force distribution to the resonator design is being developed to assist scale-up of ultrasonic particle retention devices.

INTRODUCTION

Particle separation by ultrasonic forces has several advantages relative to conventional methods, particularly in biotechnology: no physical barrier is required, there are no moving mechanical parts, hold-up times are low and chemical flocculants are not necessary. Trampler et al. (1) demonstrated 98% separation efficiency of cells from the effluent stream during a continuous mammalian cell perfusion culture lasting more than one month at cell concentrations up to 6x10^7/mL. In this continuous separation system, particles collected at the nodal planes of the standing wave field due to the axial primary radiation force (PRF). The transverse PRF aggregated the particles within the nodal planes and retained them in the field against the flow-induced drag. The axial and transverse PRF are functions of the acoustic energy density distribution. In this work, the relationship between the velocity amplitude distribution of the transducer and reflector surfaces, and the energy density distribution in the liquid is examined.

RESULTS AND DISCUSSION

A heterodyne laser interferometer was used to measure the nanometer level displacement amplitude distributions for the transducer and reflector surfaces of an ultrasonic resonator. The transducer velocity amplitude (FIGURE 1) was generally highest in the center and lowest near the edges with a superimposed grid-like pattern of amplitude maxima. The characteristic wavenumber of this variation, determined by Fourier analysis, was 6870 m^-1. The

FIGURE 1. Transducer surface velocity amplitude for the resonator is represented as a linear 128-level grayscale map with black representing maximum amplitude.
FIGURE 2. Liquid velocity amplitudes (circles) along line \((x, 3.8, 0)\) are compared to transducer (dashed line) and reflector amplitudes (solid line) along \(y=3.8\). All values normalised to \(P = 30\) W/L, \(Q = 5000\).

The corresponding standing wave speed of 2100 m/s coincides with the speed of the transverse wave in the piezoceramic. Measurements of the glass reflector amplitude revealed a similar grid pattern characterized by a wavenumber of 4700 m\(^{-1}\). The wave speed of 3100 m/s is close to the transverse wave speed in glass of 3280 m/s.

The acoustic energy density \(E_{\text{ac}}\) was determined in the liquid as a function of transverse \((x, y)\) and axial \((z)\) position (see inset FIGURE 1) from measurements of the axial PRF on 10.2 \(\mu\)m diameter polystyrene particles. The PRF was calculated from the induced particle velocities using a microscope-based imaging system (2). The liquid oscillation velocity amplitude is plotted in FIGURE 2, as calculated from the \(E_{\text{ac}}\) measurements performed mid-way between the transducer and reflector \((z = 0)\) along the line \(y = 3.8\). The liquid amplitude closely followed the overall trend in the transducer and reflector amplitudes.

The local variations in the reflector and transducer amplitude profiles apparent in FIGURE 2 demonstrate the effect of transverse standing waves. Local variations in the liquid velocity amplitude were determined from polystyrene particle velocities based on the linear relationship between the transverse PRF and the energy density gradient (2). The magnitude of the variation near the walls was found to be equivalent to that near the center of the resonator. The distance between maximum amplitude loci in the liquid was found to average 1.3 mm. This interval is equivalent to the distance between adjacent maximum amplitude points on the glass reflector surface and the interval expected to exist on the glass-water interface of the transducer.

The reflector and transducer behave as though stationary boundary conditions for the axial compression wave were imposed along their edges, resulting in a liquid velocity field with high amplitude near the center and zero amplitude near the walls. The excitation of the reflector and transducer glass with surface shear waves generates an important part of the local variations in \(E_{\text{ac}}\) giving rise to the transverse PRF. Despite the low \(E_{\text{ac}}\) near the walls, ultrasonic particle separation remains effective because the magnitudes of the local \(E_{\text{ac}}\) gradient maxima are relatively constant with position in the resonator. This view of the \(E_{\text{ac}}\) distribution simplifies modeling of particle aggregation and retention by ultrasonic forces, permitting the liquid to be treated as a collection of regular volumes each containing one \(E_{\text{ac}}\) maximum. The transverse position of the volume determines the axial PRF on particles, while the transverse PRF distribution is equivalent in each volume. Combined with modeling of particle aggregation, resonators can be designed with the required \(E_{\text{ac}}\) distribution for specific applications by selecting the appropriate dimensions and construction materials.

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REFERENCES